CO_2 ABATEMENT AND TRADE WITH ECONOMIC GROWTH IN THE LONG TERM: EXPERIMENTAL ANALYSIS

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ABSTRACT

So as to stabilize the atmospheric greenhouse gas concentrations at tolerable levels, global emissions should dramatically be reduced soon within this century. To achieve this end, a long term global cooperation and developing country participation is essential. In this paper, we take the "Contraction and Convergence" framework first proposed by the CSE (Center for Science and Environment) of India as one possible treaty and investigate the long term abatement and trading behavior of countries with economic growth. Dynamic simulation based economic experiments is the method. Seven countries with potential buyers and sellers trade permits in the global market for 25 years. For each simulated year, asks and bids of the countries /regions are collected and permit prices are set at the equilibrium price. In the first treatment, annual national quotas expire each year and the countries cannot save their allowances. In the second treatment, the countries are allowed to transfer quota surplus /deficit up to 30 /20 percent of their annual emissions to the next year. One hypothesis is that, neither the developed nor the developing countries will make sufficient timely reductions and they will create unanticipated costs for their economies as the quota prices increase over the years. An implication of this result is global cooperation being threatened under more stringent reduction requirements and increasing costs of compliance.

Keywords: international emissions trading, contraction and convergence, dynamic simulators, laboratory experiments

I. INTRODUCTION

According to economic theory, under specific conditions, an appropriate tradable-permit system can minimize the cost of reaching a predefined environmental target. In a perfectly competitive market, permits flow towards their highest-valued use. Those that would receive lower value from using the permits have an incentive to trade them to someone who would value more (Tietenberg, 2003). A tradable permit system consists of a socially agreed quota (a cap on total carbon emissions), distribution of this quota among polluters (countries /regions) and a trade mechanism under which the quota holders are free to trade their share. Under the ideal model, a polluter /appropriator will reduce down to the level where marginal cost of abatement equals the price of permit in the market. This leads to equi-marginal abatement costs, a cost effective outcome (Daly and Farley, 2004, pp. 380-81). For example, the 1992 United Nations Framework Convention on Climate Change (UNFCCC) recognizes this principle and opens the way for international emissions trading, which is now being implemented under the terms and conditions of 1997 Kyoto Protocol.

Tradable emission permit systems are analyzed by laboratory games and experiments. Bohm and Carlén 1999 analyses the cost efficiency of several emissions trade mechanisms among four Nordic countries (Denmark, Sweden, Norway and Finland). Their experiment is a one-shot bilateral trade game mimicking the negotiations under Kyoto Protocol, i.e. the countries agree to remain within their 1990 CO_2 emission levels by the year 2000. Their primary conclusion is that even a few countries can achieve high levels of trade efficiency regardless of the tested negotiation rules. Fouquet 2003 reports the results of a carbon trading game designed to help people understand the concepts of carbon trading and develop insights on how permit prices may develop. Fouchet's carbon trading game is two rounds, one following the other with renewed reduction targets and the prices are set by bi-sequential trading. Results show that international permit system does appear to save industrialized countries money and earn developing nations revenue.

Klaassen et al. 2005 describes three emissions trading experiments testing three alternative institutions: single bid and Walrasian central auctions and bilateral sequential trading. Their experiments represent the emission reduction commitments under Kyoto's first commitment period (2008-2012) and differ from the prior studies with their approach to the dynamics of price development in international carbon markets. For example, in their analysis of single-bid auctioning mechanism, Klaassen et al. collects the bids and calculates the equilibrium prices for four sequential trade rounds representing a couple of months. During the rounds of trade, the countries stay committed to a fixed reduction target ahead and confirming the economic theory, the prices converge towards the perfectly competitive equilibrium price. Moreover, they find that every country gains from trading.

Our experiments are on the long term (over 25 years) analysis of price development and trade efficiency with economic growth in the long term. We take the emissions quota allowances for individual countries granted by the global "Contraction and Convergence" scheme as our framework of analysis. Contraction and convergence (C&C) is a cap-and-trade policy with a unique transient approach to the highly debated baselines problem, i.e. at the starting year, each country is entitled to emit at its historical levels but over the years, national emission rights (carbon emission allowances) change as per capita emission rights converge towards a universally agreed, fixed equal value (Meyer, 2000). Besides, the C&C framework is in line with the basic goals of ecological-economic policy making described in Daly and Farley 2004, trying to satisfy the three imperatives: sustainable scale, just distribution and efficient allocation. In practical terms, first, starting from a target atmospheric CO_2 concentration level, a global carbon emissions contraction path (annual global emissions budget) is decided on, that satisfies the sustainable scale imperative. Then, second, a convergence date is fixed, at which global per capita emission right will become equal. This satisfies the just distribution imperative. Based on national population projections, the contraction path and the gradual convergence target together identify annual national emission quotas. Third, to reduce the costs of compliance, the annual national emission quotas are traded, satisfying the efficient allocation imperative.

C&C's long term and transient approach to the international climate policy necessitates a dynamic analysis of emitters' behavior, price development and trade efficiency. For this purpose, similar to the experiments conducted in Vogstad 2005, Moxnes 2006 and Assuad and Moxnes 2006, we make use of dynamic simulators and network games where emissions are reduced and emission rights are traded once each year over a simulated period of 25 years. Our hypothesis is that, the dynamics involved in the carbon emission rights trading system can be too complex for the policy makers to sufficiently comprehend and this can create unexpected trade costs for the buyers. Particularly, the countries observing low cost trade opportunities may evade reducing their emissions in earlier stages and soon, faced with stringent reduction goals, they may have to purchase higher amounts at increased prices. Increasing costs of compliance may threaten the viability of the global C&C scheme.

Seven countries /regions are represented in the experiments. These are the major potential buyers and sellers in the proposed global market, namely, US, China, Japan, UE, Brazil, Former Soviet Union and India which created about the 75% of global carbon emissions by year 1985.[1] To test our hypothesis we run economic experiments on two institutions. The first treatment (T0) does not allow any banking and deficit of emission rights and the annual allowances expire each year. The second treatment (T1) allows the countries to transfer quota surplus /deficit up to 30 /20 percent of their annual emissions as assets to the next year. Every year, the "asks" and "bids" are submitted by these seven participating countries and the market is cleared at the equilibrium price.

The next section introduces the model. Third section is on the experimental design. Fourth section presents the results and their analysis. The paper concludes with a discussion on findings and insights generated by the game and data analysis.

II. MODEL

The *Carbon Emissions* and *Emission Quotas* accumulation structure for each country /region is represented by a two stock (second order) dynamic model (Figure 1). Model works on annual basis on discrete time steps, i.e. the emissions reduction and /or quota selling/ buying decisions are taken each year and the *Carbon Emissions* and *Emission Quotas* are updated annually. *Carbon Emissions* grow according to a fixed business as usual *BAU growth fraction* and *reduce* according to the country's annual carbon abatement strategy. The business as usual (BAU) growth in emissions stands for the inertia of the system due to economic growth and slow replacement of existing traditional capital under the absence of any specific abatement strategy. Growth fraction is set to 1.5% per year for US, Japan, EU and FSU and 3% per year for China, Brazil and India.[2] Note that, *reduction* is the player's decision interacting with the simulation game. Therefore:

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[1] These seven country /regions are chosen from twelve categories adopted by EPPA Model (Yang. Z., R. S. Eckaus, A. D. Ellerman and H. D. Jacoby. 1996. The MIT Emissions Predictions and Policy Analysis Model. Report 6. Cambridge, Massachusetts: MIT Joint Program on the Science of Global Change, May). According to the EPPA reference analysis, by year 2010, these regions will be emitting 66% and by year 2050, 61% of global carbon, hence they cover a larger share of global carbon market.

[2] Different models attribute different business as usual growth fractions for national carbon emissions. EPPA estimates that world carbon emissions will grow by an annual average of 2.1% if specific political measures are not taken, while POLES's estimate for the same variable is 1.8% (Criqui, P., M. Silvana, L. Viguer. 1999. Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model, *Energy Policy* 27: 585: 601). The dissaggregation of these global growth fractions among North and South countries (in Kyoto's terminology, among Annex B and non-Annex B countries) by both models show lower BAU growth fractions in the North and higher BAU growth fractions in the South.

(1) Carbon Emissions(t+1)=Carbon Emissions(t)+Carbon Emissions(t)*BAU growth fraction–reduction

Carbon emissions are initialized for each country /region to its value in year 2000 based on the data sourced from Carbon Dioxide Information Analysis Center (CDIAC) in 2003 by Global Commons Institute's (GCI) contraction and convergence simulator available from GCI's web site.[3] In the next section, however, we shall see that the gaming functionality is set to start in year 2005 rather than 2000 since the experiments are performed in year 2005 and 2006.

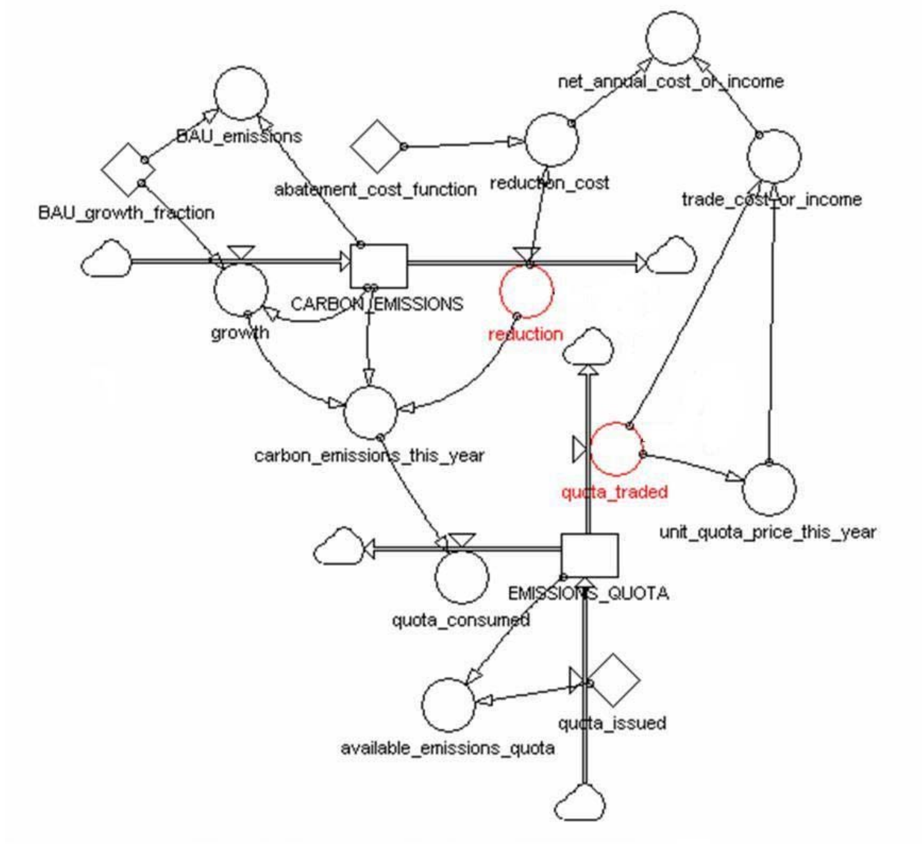

Figure 1. The simulation model.

Emission Quotas increase as quotas are issued for each year according to the exogenous contraction and convergence scenario; increase or decrease as they are sold or purchased in the market; and decrease as they are consumed, i.e. as carbon emissions are realized for that year. Note that quota traded is the player's decision. Therefore:

(2) Emission Quotas(t+1)=Emission Quotas(t)+quota issued+quota traded–quota consumed

[3] Global Commons Institute – Contraction and Convergence, copyright 1997-2003, www.gci.org.uk.

This accumulation structure is effective if quotas can be transferred over the years. In the first experimental treatment (T0), quotas expire each year. Hence, the stock *Emission Quotas* disappear and *available emissions quota* becomes an algebraic sum of *quota issued* and *quota traded*. In the second treatment (T1), countries /regions are allowed to transfer a surplus up to 30% or a deficit up to 20% of their emissions for that year. In this case *Emission Quotas* is a stock (an asset) that can be transferred over the years.

Quota is issued according to an exogenous contraction and convergence scenario. National /regional carbon emission quotas based on alternative contraction and convergence scenarios can be studied on CGI's C&C simulator. Each C&C scenario needs to be based on several assumptions about a target atmospheric CO_2 concentration; a contraction year at which the global carbon emissions is reduced to the target emissions level; a convergence year at which the per capita carbon emission rights become equal; and a population cut-off year, after which further population growth does not account to a further increase in national /regional emission rights. The contraction and convergence scenario adopted in our analysis assumes a target atmospheric CO_2 concentration at 450 ppm, contraction at 75 years ahead and convergence and population cut-off year at 40 years ahead. To be consistent with EPPA, the national emission quotas calculated in CGI's C&C simulator is aggregated for the EU and FSU.[4] The calculated annual emission quotas for the seven countries /regions are illustrated in Figure 2.

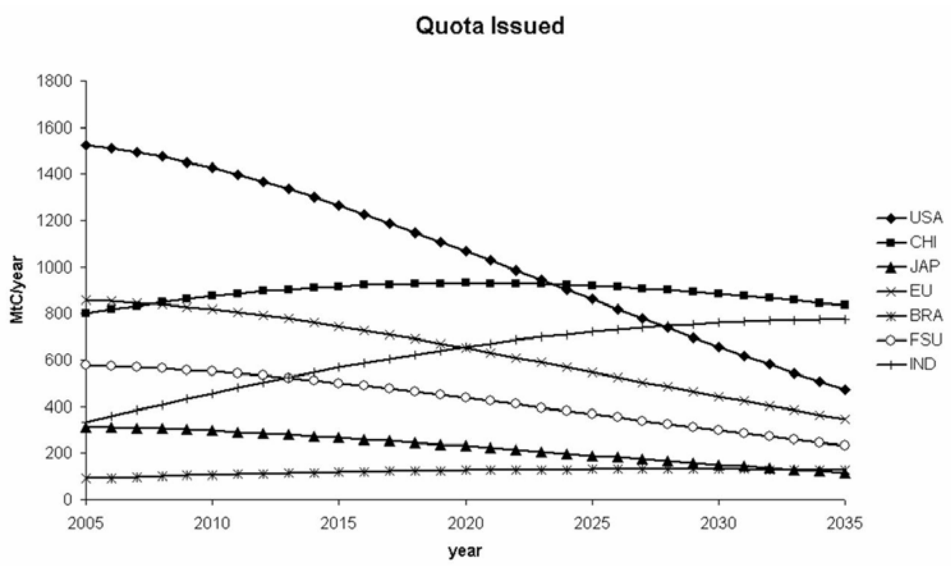

Figure 2. Annually issued national /regional carbon emission quotas.

[4] EU aggregates the 15 member states until year 2004 (France, Italy, Germany, Belgium, Holland, Luxemburg, England, Denmark, Ireland, Greece, Spain, Portugal, Austria, Sweden and Finland). FSU aggregates Russia, Ukraine, Latvia, Lithuania, Estonia, Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldavia, Tajikistan, Turkmenistan, and Uzbekistan. "The Ideas and Algorithms behind Contraction and Convergence and Alternative C&C Options" is available on www.gci.org.uk.

Unit quota price is set at each round according to the quota demand and supply in the market. The simulator collects asks and bids from the seven participating countries /regions and calculates the price at which total demand equals total supply. Each country /region offers five alternative prices for five alternative supply and /or demand quantities. For each price offered by seven players, individual supply /demand quantities are calculated by piecewise linear interpolation. Then the aggregate supply and demand curves are constructed. Since the asks and bids are submitted as decreasing supply /increasing demand with decreasing prices, multiple equilibrium on the aggregate supply-demand curve is avoided. The price where demand equals supply (the equilibrium) is decided by piecewise linear interpolation between the two prices corresponding to the lowest over-demand and lowest over-supply. In case such equilibrium is not found, there is either over-supply or over-demand. For over-supply case, price is set at the minimum price offered; the over-supply at this price is distributed over all suppliers in proportion to their individual supply quantities at that price. For over-demand case, price is set at the maximum price offered; the over-demand at this price is distributed over all demanders at that price in proportion to their individual demand quantities.

Abatement cost calculations are based on marginal abatement cost curves generated by EPPA general equilibrium model and sourced from Ellerman et al., 1998. These curves represent the marginal abatement costs (or shadow prices) corresponding to alternative fractional emission reductions by year 2010. The prices are given in 1985 US$. Ellerman et al., 1998 creates quadratic fits for these MAC curves and their integrals stand for the total abatement costs corresponding to alternative fractional emission reductions by year 2010. Figure 3 illustrates these marginal abatement cost curves for the seven EPPA regions chosen for our experiments. Indeed, adopting these EPPA curves in the current dynamic model arises two questions: First, these curves are generated for year 2010 commitments but our time horizon is longer than this time frame under which the parameter estimates are assumed valid. Second, ours is a dynamic approach where the countries /regions reduce their emissions every year according to their annual commitments, i.e. with respect to the quota available to them for that year. By doing that, compared to their static abatement costs, regions benefit from early reductions as it slows down their future emissions growth and reduces their total reductions (hence, total costs) as they try to achieve a fixed emissions target. On the other hand, our purpose is not a precisely calculation of the abatement costs, but what is important is the relative magnitude of abatement costs of different regions and their characteristic functional forms. As long as the relative magnitudes and the characteristic functional forms do not change for the dynamic and static calculations, our choice of abatement cost functions should be valid.[5]

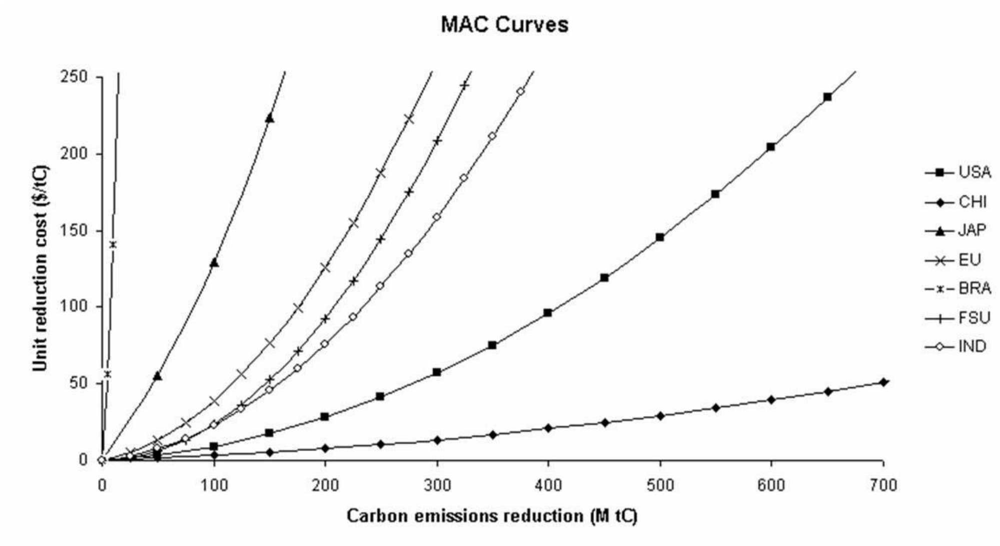

Figure 3. EPPA Generated Marginal Abatement Cost Curves - 2010.

The model calculates the abatement costs and costs /benefits from trade every year. Abatement cost is the area under the *abatement cost function* integrated over the *reduction* for that year. *Trade cost /income* is the *quota traded* multiplied by the *unit quota price* for that year. Their sum is the *net annual cost /income*.

III. EXPERIMENTAL DESIGN

The experiments are based on the dynamic model designed as a seven player network simulation game. In this section, first the simulator interface and the game institutions are introduced. After that, the subjects' tasks and objectives are described. Last sub-section is on the subject groups and treatments.

III.1. Simulator Interface and the Institutions of the Game

The simulator is implemented on *Powersim Constructor* (Powersim, 2000). Figure 4 is the simulator interface for the second treatment where banking /deficit of emission quotas are allowed. With minor modifications, this interface is applied for the first treatment as well.[6]

[5] The simulator takes annual BAU growth fractions 1.5% and 3% for the developed and developing countries respectively. When no-trade dynamic costs for 25 years are compared to static costs calculated for the same target emissions level, these percentages correspond to approximately 1.3% and 2.8% BAU growth assumptions respectively for their MAC curves. That is, if the MAC had assumed 2.8% for a developing country /region such as China, then the resulting abatement cost calculated by the simulator based on 3% annual growth for the next 25 years would be equal.

[6] In the first treatment T0, emissions quota is not a stock. Therefore, in "This Year" frame in the interface, "Available emissions quota" disappears. Similarly, in "Last Year" frame, "Emissions quota" disappears. In T0,

The upper left frame presents information for the current year. *Issued emissions quota* (MtC) stands for the annual amount allocated according to the C&C plan. *Available emissions quota* (MtC) is the net amount with the surplus /deficit transferred from the previous year. *BAU emissions* represent the business as usual emissions that will occur by the end of current year. For the regions, US, Japan, EU and FSU, *BAU Emissions* (MtC) is 1.5% over last year's emissions, while for the regions China, Brazil and India, it is 3% over. For each year, the difference between the *available emissions quota* and *BAU emissions* has to be managed within the acceptable quota surplus /deficit limits which is set as 30 /20% of last year's emissions respectively for the current game. Any year, no country can reduce more than 5% of their emissions (illustrated by *maximum possible reduction*), because a reduction beyond this amount is highly unrealistic from technological and political perspectives. The *trade range* (MtC) depicts the possible range of sales /purchases that can be realized for that year without violating the country's annual commitment to the C&C treaty. Positive values stand for purchases and negative values for sales.

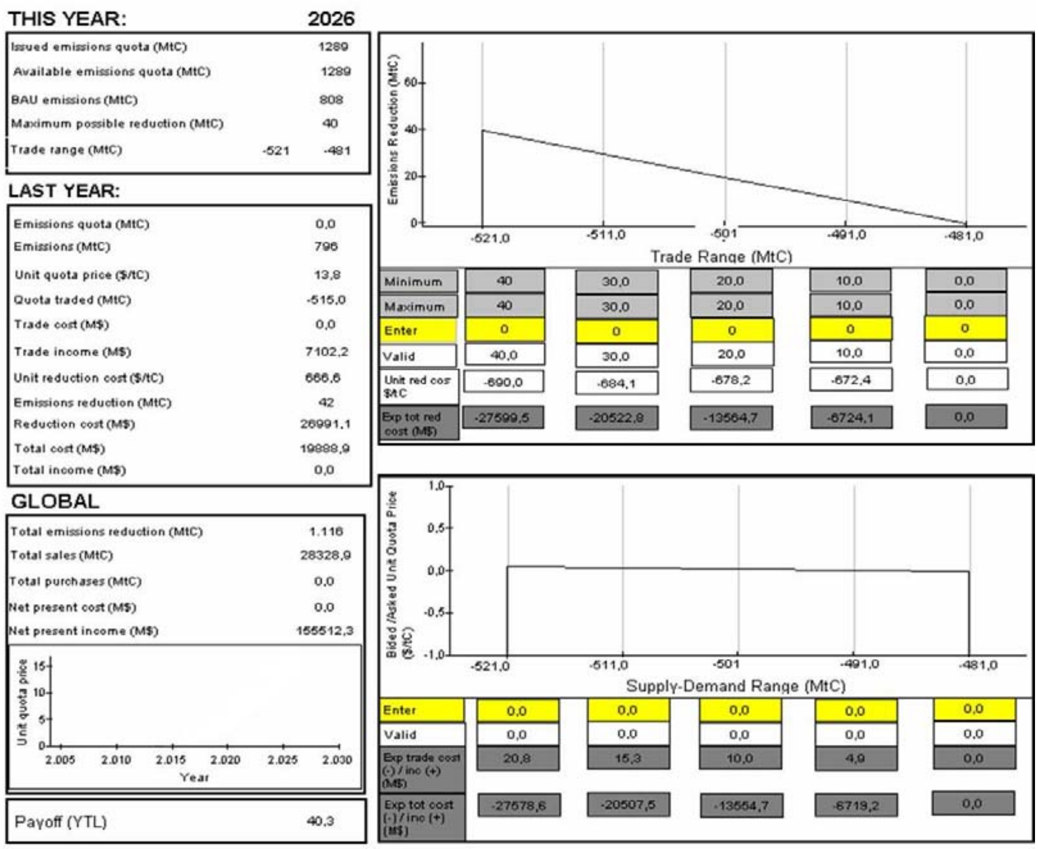

Figure 4. Simulator interface.

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the single constraint on the maximum of emissions reduction corresponding to every trade alternative is equal to the %5 of BAU emissions, representing an assumption on the limits of reduction dictated by the technological and political factors. Hence, the "maximum" row below the first graphical input device disappears as well.

For every possible trade amount within this range, there is a minimum and a maximum reduction amount (a reduction range) that needs to be satisfied so that the country can comply. With this design bringing annual limits to the trade range and to the corresponding reductions, penalty due to non compliance is ruled out. Simulator calculates the trade range with respect to the formula:

(3) $0.8\times(\text{BAU\_emissions}-\text{reduction})-\text{Emissions\_Quota}-\text{quota\_issued} \leq \text{quota\_traded} \leq 1.3\times(\text{BAU\_emissions}-\text{reduction})-\text{Emissions\_Quota}-\text{quota\_issued}$

While calculating the trade range, for maximum sales, set reduction equal to maximum possible reduction, that is, %5 of BAU emissions. For maximum purchases, set reduction equal to minimum reduction, that is equal to 0:

(4) $\text{maximum\_sale}=0.8\times(\text{BAU\_Emissions}-0.05\times\text{BAU\_emissions})-\text{Emissions\_Quota}-\text{quota\_issued}$

(5) $\text{maximum\_purchase}=1.3\times\text{BAU\_emissions}-\text{Emissions\_Quota}-\text{quota\_issued}$

Between the maximum sale (negative) and maximum purchase (positive) values, three more trade alternatives are created. The choice is such that, if the trade range covers sales and purchases, then there is one no-trade alternative and the other two is set as half of maximum sale and half of maximum purchase values. Else if only sales or only purchases are possible, then the three more trade alternatives are calculated with equal increments within the trade range. In both cases, together with the two extremes, five trade alternatives are calculated.

The minimum and the maximum reductions corresponding to each of the five trade alternatives are calculated. In equation (3), inserting minimum reduction for reduction on the left hand side of the inequality, and inserting maximum reduction for reduction on the right hand side of the inequality:

(6) $\text{minimum\_reduction}=\text{BAU\_emissions}-(\text{quota\_traded}+\text{Emissions\_Quota}+\text{quota\_issued})/0.8$

and

(7) $\text{maximum\_reduction}=\text{BAU\_emissions}-(\text{quota\_traded}+\text{Emissions\_Quota}+\text{quota\_issued})/1.3$

In the first treatment T0, since quota surplus /deficit transfer is not allowed, i.e. *Emissions Quota* is 0, (4) and (5) reduces to:

(8) maximum_sale=BAU_Emissions-0.05×BAU_emissions–quota_issued

(9) maximum_purchase=BAU_emissions–quota_issued

For the minimum and the maximum of reduction amounts in T0, (6) and (7) reduces to:

(10) minimum_reduction=BAU_emissions–quota_traded–quota_issued

(11) maximum_reduction=0.05×BAU_emissions

The middle left frame presents information realized last year. *Emissions Quota* represents the quota surplus or deficit transferred to the current year. *Emissions* (MtC) , *unit quota price* ($/tC), *quota traded* (MtC, negative for sales and positive for purchases), *trade cost* or *trade income* (M$), *unit reduction cost* ($/tC), *emission reduction* (MtC), *reduction cost* (M$), *total cost* or *total income* (M$) appear in order in this frame.

The lower frame keeps track of global indicators accumulated up to the current year in simulation. These are *total emissions reduction* (MtC), *total sales* (MtC), *total purchases* (MtC) and *net present cost* (M$) or *net present income* (M$). Net present cost /income is the 3% discounted accumulation of costs /incomes generated each year and is the basis of subjects' payoff calculation.

Subjects enter their reduction decisions on the upper right graph. The horizontal axis is the trade range calculated by Equations 4 and 5. The vertical axis is the corresponding emissions reduction choices. The design of this graphical instrument avoids the subjects enter decisions violating their commitments to the treaty. The *minimum* and *maximum* reductions corresponding to the trade amounts on the horizontal axis (calculated by Equations 6 and 7) are presented on the first two rows below the graph. Underneath, subjects *enter* their decisions within this range. In case an invalid decision is entered, the simulator corrects the subject's choice and presents a valid choice on the row labeled *valid*. Hence, the subjects are urged to check the consistency of their choices by observing the equality of the values that appear on the two rows labeled *enter* and *valid*. Below these rows, subjects are able to observe corresponding *unit reduction cost* ($/tC) and *expected total reduction cost* (M$) of their choices. The graphical representation of subjects' choices helps them see that the simulator linearly interpolates the values in between their entered valid choices.

The lower right graph helps the subjects submit their asks and bids to the market. The horizontal axis is the supply-demand range that is exactly equal to the trade range of the previous graph (supply negative values, demand positive values). Vertical axis is the asked

/bided unit quota price ($/tC). Subjects are allowed to enter any price provided that they submit decreasing prices with decreasing supply and increasing demand. If they fail to obey this rule, the simulator modifies their choice on the *valid* row. Hence, here again, subjects are urged to check the consistency of their choices by observing the equality of values on *enter* and *valid* rows. *Expected trade cost /income* for these choices appear below. Under that, *expected total cost /income* is the sum of emission reduction cost calculated on the previous graph and the trade cost /income. The graphical representation of the asks and bids mean that the simulator linearly interpolates the values between subjects' effective choices. The ask at the left most corner of this graph means, the subject is eager to sell that amount at any price over his entered price choice. The bid at the right most corner of this graph means, the subject is eager to buy that amount at any price below his entered price choice.

These two graphs help the subjects finalize their alternative reduction and trade choices before submitting their asks /bids to the central auctioneer. Once they decide (on all alternative trade-reduction combinations and asks and bids), they submit by hitting a button on the screen, then the simulator receives the information, calculates the equilibrium price and realizes the corresponding trade and reduction amounts for the seven players (as described in Section II). Simulator advances one time unit (one year).

III.2. Task and Objective

The subjects' task is to comply the C&C treaty over the 25 simulated years between year 2005 and 2030 by annually reducing her /his emissions and /or selling /buying emissions quota in the international carbon market. Their objective is to minimize their *net present cost* or to maximize their *net present income* that accumulates discounted annual *total costs* or annual *total incomes*. To create a controlled economic environment, confirming the principles of economic experiments (Smith, 1982) subjects are rewarded money in proportion to their success in achieving their objective. No-trade net present costs (for example, imposed taxes) of individual countries are used as a reference for calculating the subjects' payoffs. Depending on their commitments under C&C, all countries except India have no-trade abatement costs. In our design, India is an exception since its business as usual emissions growth trajectory (3% annual growth) is still below its C&C emission rights in year 2030. Among others, particularly China has a large trade income potential since its annual quota allocation follows an increasing pattern and its abatement costs are much lower than the others'. To achieve a relatively fair distribution, the payoff formulation takes these particularities into account. The subjects receive a base fee of 40 YTL (about two hours wage of a student) for joining the experiments and receive monotonically increasing monetary rewards as they perform equal to and better than their no-trade *net present costs*.[7]

III. 3. Subjects and Treatments

Two trials of each treatment were performed with 28 senior and graduate engineering students in Boğaziçi University, İstanbul. They received five pages instructions of the game few days in advance. Before the sessions, the experiment leader had a one hour presentation on the context, task and rules of the game and on the practicalities of the simulator. Subjects did not know what country they represent; the emissions quota trajectory information was public and abatement cost information was private. Since the purpose is to assess the subjects' long term strategic behavior, to avoid last round decisions being particularly short time oriented (such as, buy as much quota as you need rather than reducing; or sell as little as you can rather than reducing) the experiments were stopped five periods earlier than it was instructed. For each experimental session, the interactive simulation of 25 years took about two hours.

IV. RESULTS

In this section, we shall first present a no-trade behavior of the regions and associated costs of reduction. Then, for the first treatment (T0), we shall model a minimum reduction strategy for potential buyers and sellers, i.e. they seek equi-marginal abatement costs under this strategy (so called efficient trade) at each round of trade and present the simulated results. After that, first minimum reduction strategies and then maximum reduction strategies of the traders will be modeled for the second treatment (T1), again as they seek equi-marginal abatement costs. Here, while the first corresponds to a maximum deficit strategy, second corresponds to a maximum surplus strategy at each round of trade. Lastly, the simulated and experimental results for T0 and T1 will be compared and discussed.

Efficient trade assumes, at each round, subjects want to reduce their emissions up to the unit where their marginal abatement cost equals unit emissions quota price that they can get from the market; then, either sell or buy the required quota amount to comply the treaty. Then, depending on the price that they are able to get, they decide on how much to trade and how much to reduce to comply. This rationale is illustrated on a hypothetical MAC curve (Figure 6). If trade was not an option, the country would have to reduce its emissions to the quota

[7] For all countries except India, Payoff=40+$a \times b^{-(NPC/NTNPC)}$; NPC: net present cost; NTNPC: no-trade net present cost; a and b are positive integer parameters adjusted for each country. For India, Payoff=40+$c \times$(-NPC/M); c is a positive integer parameter calibrated for India and M is the income generated by India w.r.t. minimum reduction strategy described in Section IV.2.

level and the reduction cost would be equal to the area a-b-f-e. If trade is an option, for any unit quota price, the country should be eager to reduce to the level where unit reduction cost equals unit quota price, P_e. Then, the discrepancy between the reduced amount and the available quota is either sold or purchased. In this case, the area a-b-c-d represents the cost of reduction and the area e-g-c-d represents the trade income. Therefore, the area f-g-c is the net gain from trade.

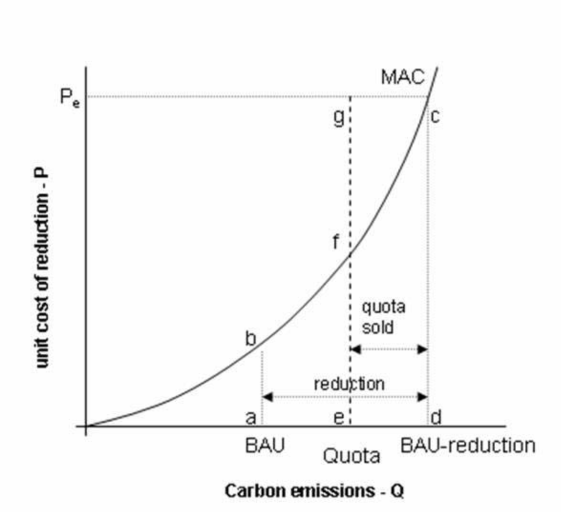

Figure 6. MAC and unit quota price.

IV. 1. Abatement without Trade

Figure 5 illustrates the emissions abatement without trade, under tax for example. The countries exactly follow their issued quotas unless their BAU emissions are below. Otherwise, they follow their BAU emissions path (as observed for India). Simulated net emissions reduction (initial emissions minus emissions at year 2030) and net present costs of reduction (accumulation of discounted net annual costs or incomes at year 2030) are tabulated on Table 1.

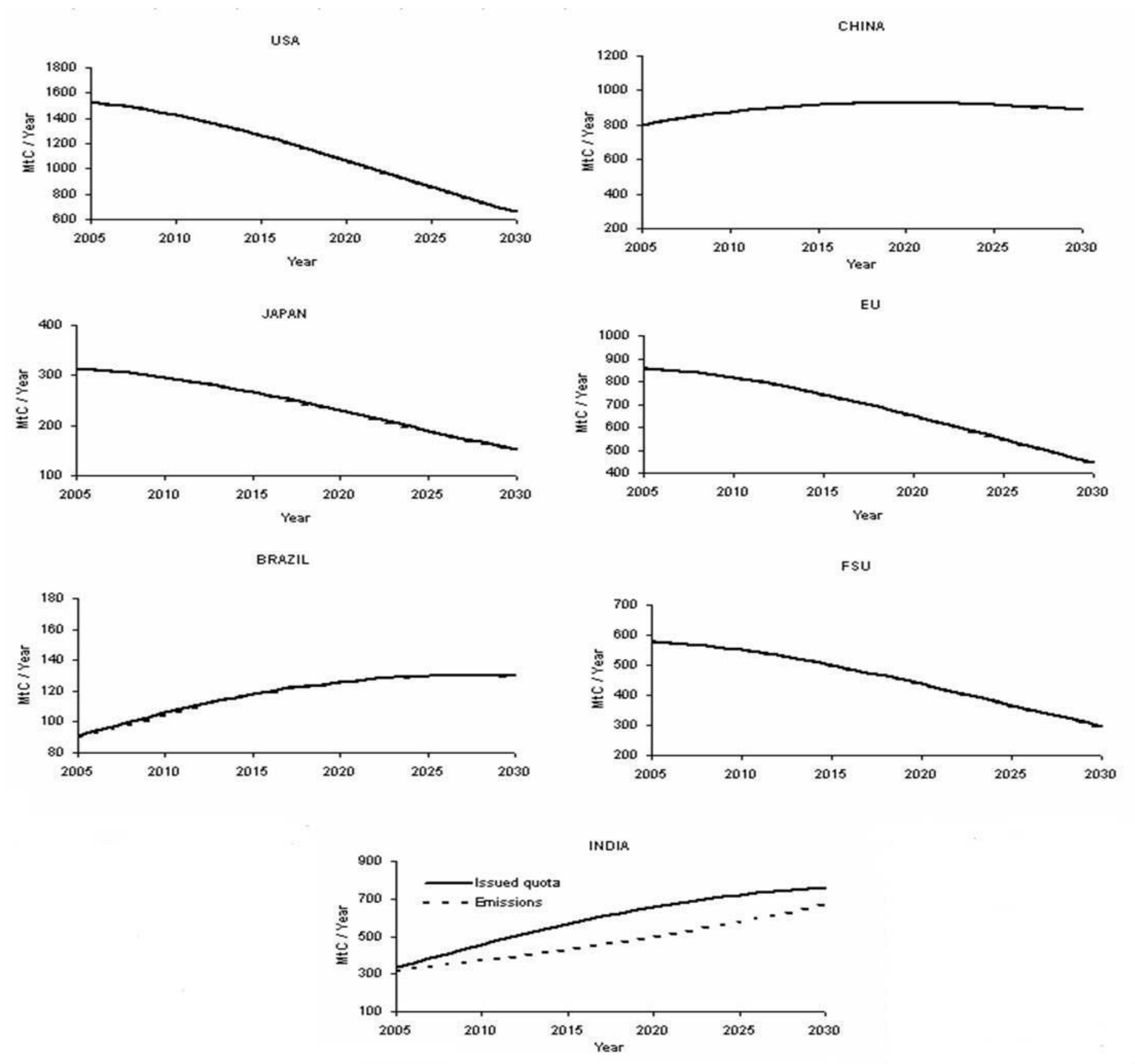

Figure 5. Emissions path without trade.

IV. 2. T0 Minimum Reduction Strategy

This behavior is modeled as follows: For each country /region, the simulator calculates three equidistant alternative trade quantities within the trade-range calculated by Equations 8 and 9. Together with the two extremes, that makes five alternative trade quantities (T_{ij}; i=1..7, j=1..5). For all T_{ij}, corresponding minimum reductions ($R_{ij,min}$) are calculated by Equation 10. For all $Rmin_{ij}$, the simulator calculates the corresponding unit reduction costs ($P_{ij,min}$) based on the MAC curves depicted in Figure 3. Then the T_{ij}-$P_{ij,min}$ combinations are assembled to calculate the market equilibrium price P_e as described in Section II. Note that, in Treatment 1 with banking and deficit, this corresponds to a maximum deficit strategy. Alternatively, corresponding minimum reductions $R_{ij,min}$ can be substituted with corresponding maximum reductions $R_{ij,max}$ calculated to test the maximum surplus strategy.

After calculating the equilibrium price, the trade amounts (*quota traded*$_i$) are calculated. Then, corresponding reductions (*reduction*$_i$) are realized:

(12) reduction=BAU_emissions–(quota_traded+quota_issued)

In T1, following (3), for minimum reduction, this is replaced by

(13) reduction=BAU emissions–(Emissions Quota+quota traded+quota issued)/0.8

and for maximum reduction

(14) reduction=BAU emissions–(Emissions Quota+quota traded+quota issued)/1.3

Figure 7 illustrates the emission behaviors under above formulation.

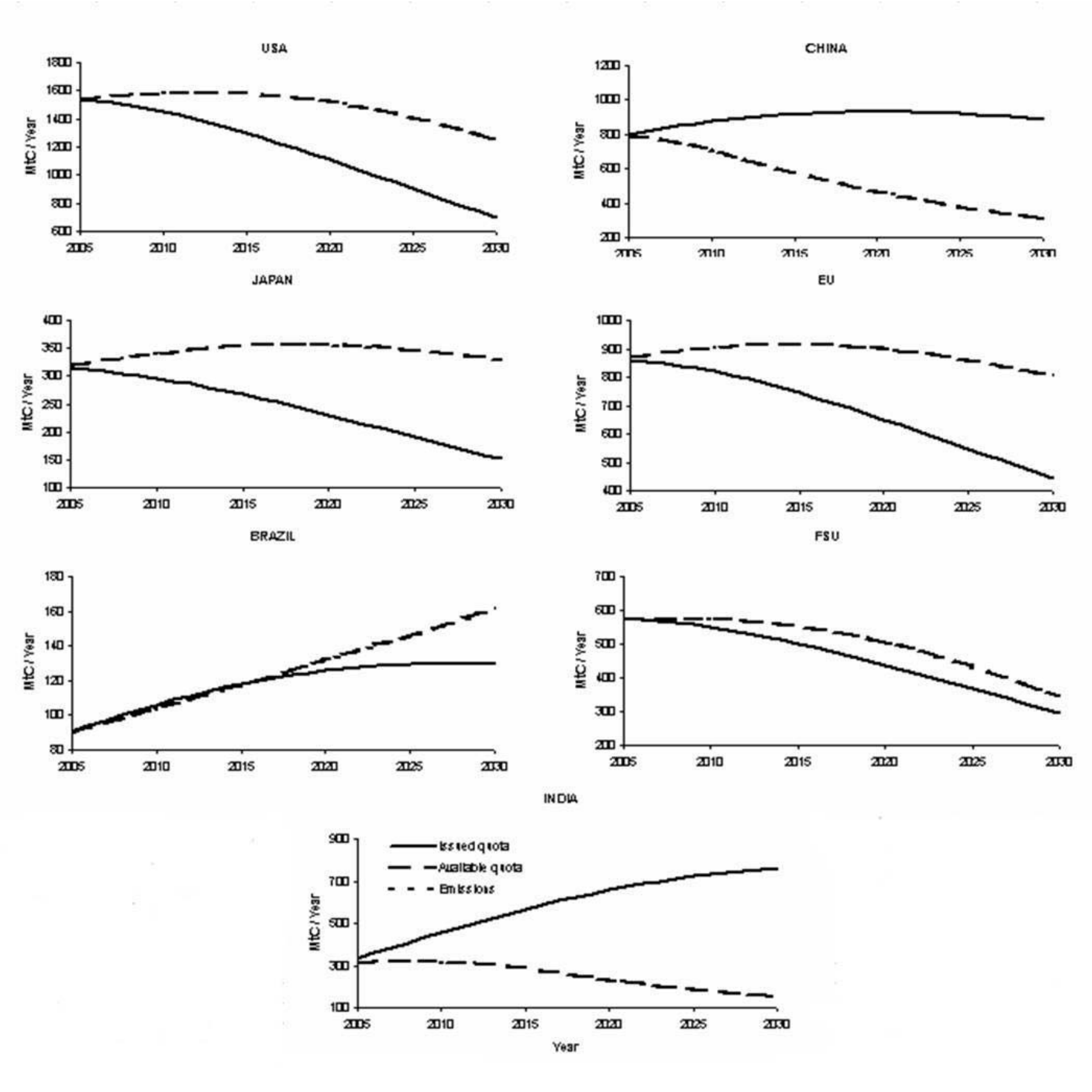

Figure 7. Country behaviors and price development in T0-Min.

Price development is illustrated in Figure 8.

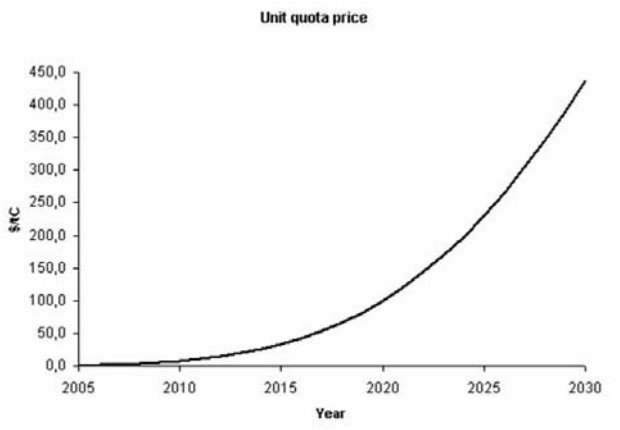

Figure 8. Price development in T0-Min.

Table 1 illustrates several parameters associated with the simulations and experiments. Net reduction (MtC) is the difference between emissions at year 2005 and 2030; negative values mean emissions have increased. Net present cost (M$) is the discounted total costs /benefits over 25 years; negative values mean income. Quota slack (MtC) is the difference of available quota and emissions at year 2030. Net total trade (MtC) is the total trade (both sales and purchases) achieved by an individual country. Total global trade is either total sales or purchases (which are equal) realized by all countries. Therefore, the last row of this column is not its algebraic sum.

In T0 minimum reductions (T0-Min), US, JAP, EU, BRA and FSU appear as buyers and CHI and IND appear as sellers as expected. When the T0-min is compared to abatement without trade, all buyers assume higher costs and all sellers assume higher incomes. That is, all buyers loose and all sellers gain from trade. In abatement without trade total emissions decrease by 1081,8 MtC in 30 years while in T0-min, it decreases by 976 MtC. This is because, the slack available to India in the case without trade is traded to the potential buyers. When the overall costs and benefits are considered, the total cost of abatement with T0-min is still higher.

IV. 3. T1 Maximum Deficit and Maximum Surplus Strategies

The minimum reduction strategy is modeled for T1, which implies submitting bids trying to hold maximum allowed deficits. Emission and quota behaviors are illustrated in Figure 9. Again, the sellers are China and India.. Price development is not different from development in T0-Min, and is illustrated in Figure 10.

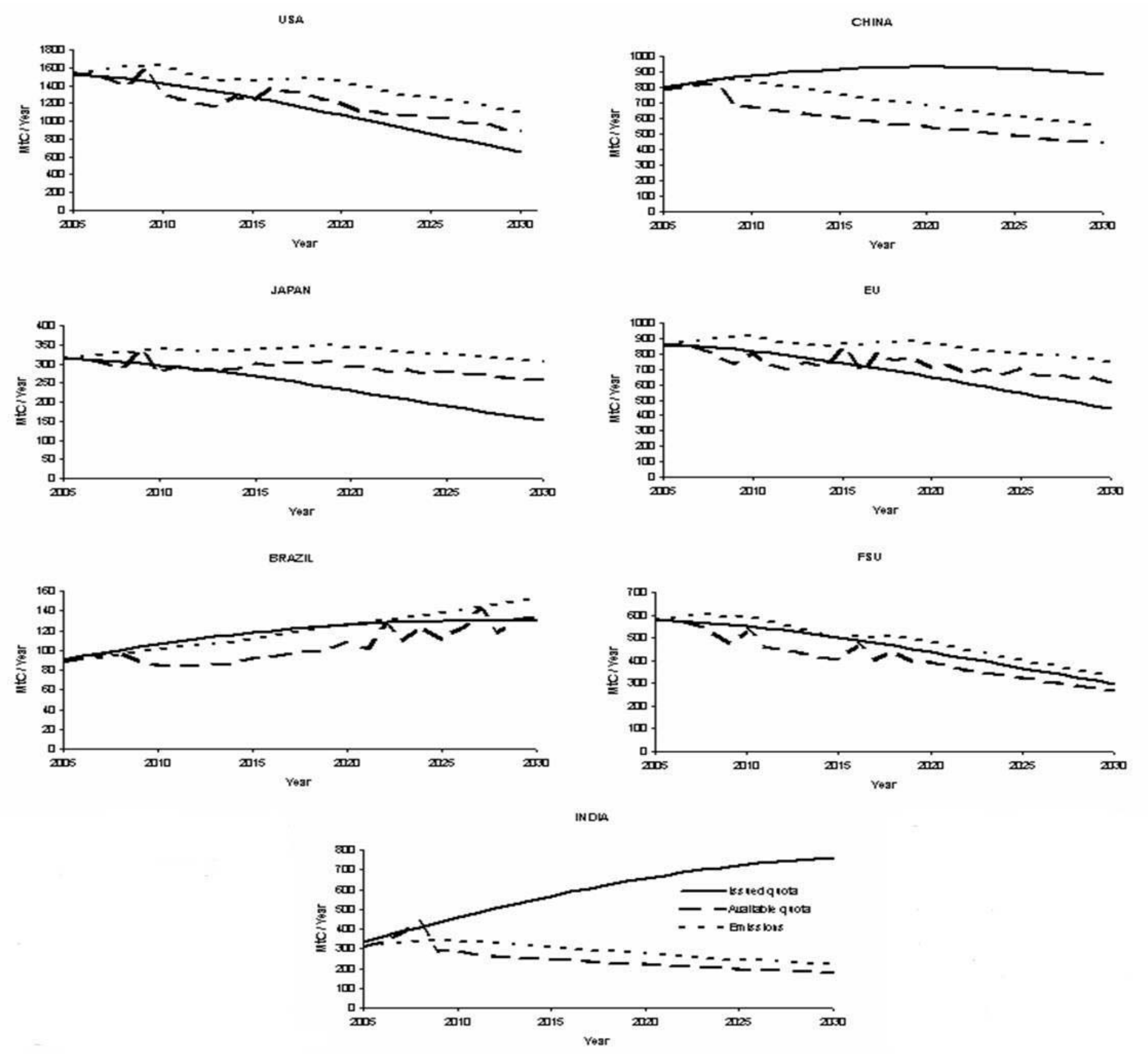

Figure 9. Country behaviors and price development in T1-Min.

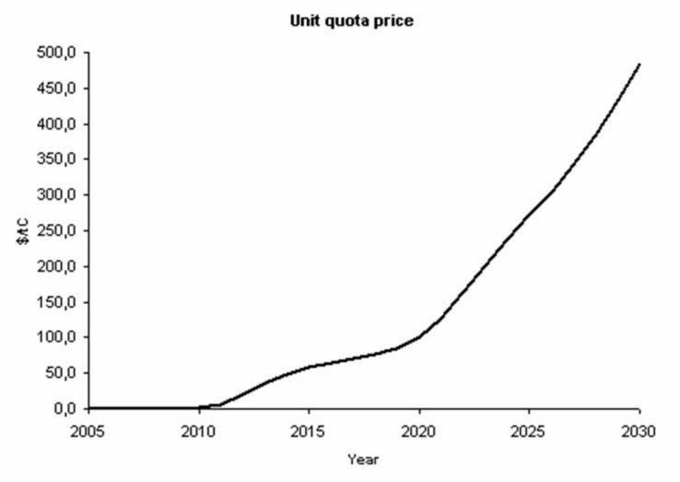

Figure 10. Price development in T1-Min.

T1-Min is tabulated on Table 2. Total net emission reduction is about 100 MtC less and net total trade is about 5000 MtC less than that for T0-Min. Again, none of the buyers can benefit from trade.

Figures 11 and 12 illustrates the developments for T1-Max, which implies submitting bids, trying to hold maximum surplus. Price development is not different. China and India are the sellers. T1-Max is tabulated on Table 2. Net total reduction and net total trade are close to those for T0-Min, costs and benefits are close to those for T1-Min and still, none of the buyers can benefit from trade while there are huge benefits for the sellers China and India.

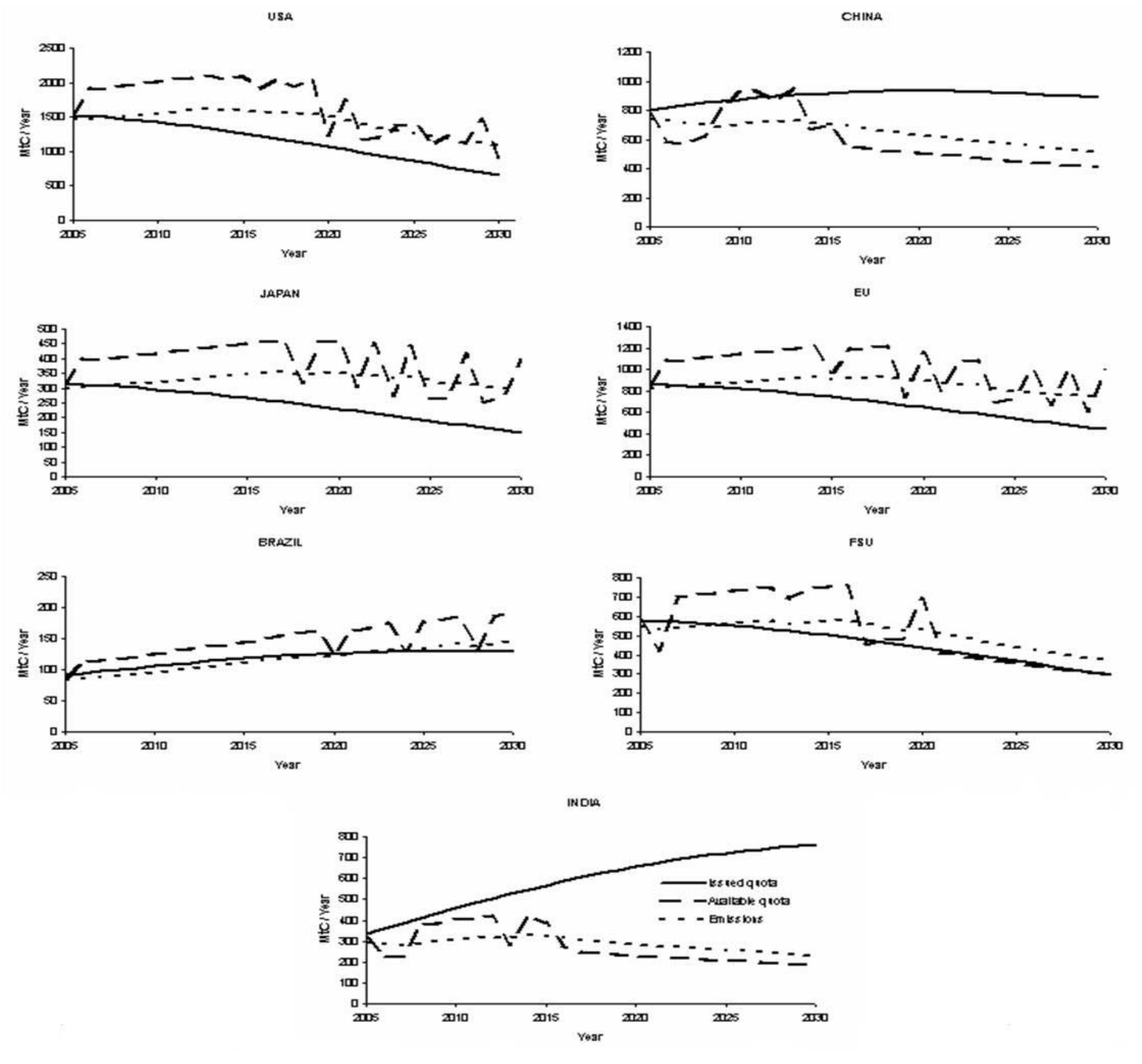

Figure 11. Country behaviors and price development in T1-Max.

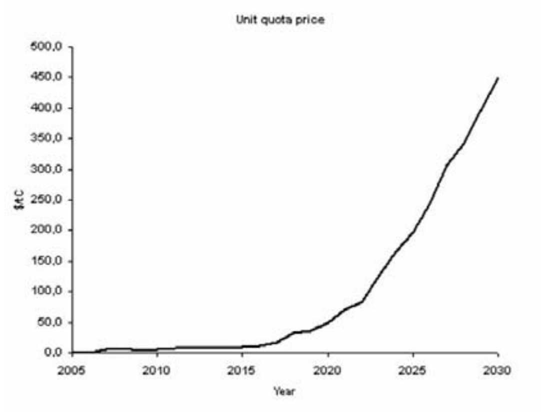

Figure 12. Price development in T1-Max.

IV. 4. Results of the Experiments – T0

In both trials of T0, all buyers are worse-off and all sellers are better-off in their net present costs compared to no-trade case (see Figure 13 and Table 1). Therefore, buyers cannot benefit from trade. However, in the second trial, the buyers are only marginally worse-off, i.e. their net present costs are closer to the values in no-trade. Total cost of the treaty is less than no-trade case for both trials, that is, there is a net transfer from the buyers to the sellers.

When both trials are compared to T0-Min, all buyers except FSU make larger reductions (see Table 1). The sellers, China and India increase their emissions. Therefore, both the demand from the buyers and the supply from the sellers become less and the size of the market shrinks. Net total trade is significantly reduced. Price follows similar patterns but significantly differ in dimension. The ET price in year 2030 is calculated as 436 $/tC. This value is close to 1000 $/tC and 350 $/tC in the first and second trials respectively (Figure 10).

Although the buyers cannot benefit from trade, they are all better-off in their net present costs compared to T0-Min. All sellers are worse-off in the same measure with respect to T0-Min. The conclusion is, buyers cannot benefit from trade but they follow timely reductions and do not assume higher costs as realized in T0-Min. Total cost of the treaty is less than that observed for T0-Min.

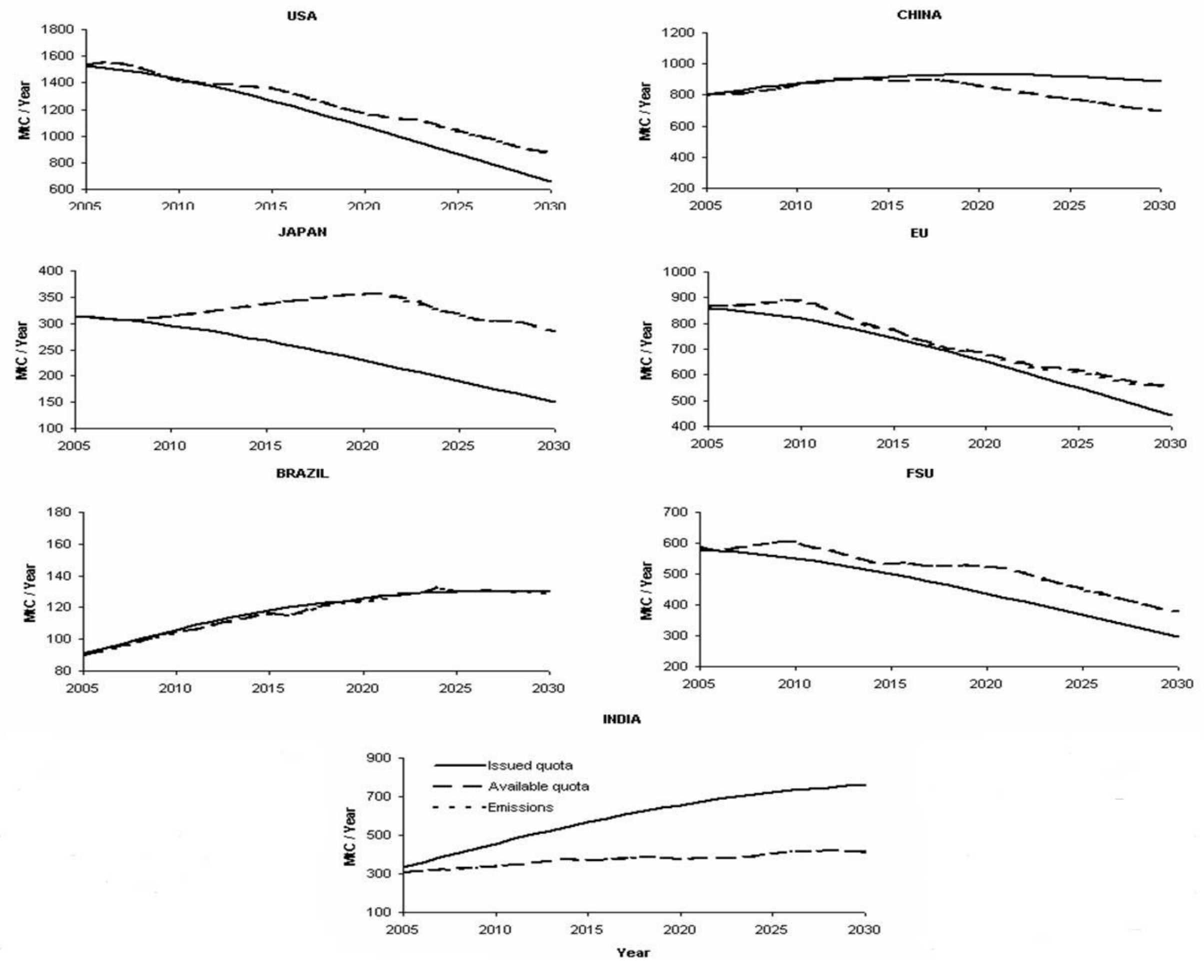

Figure 13. Country behaviors in T0, trial 1.

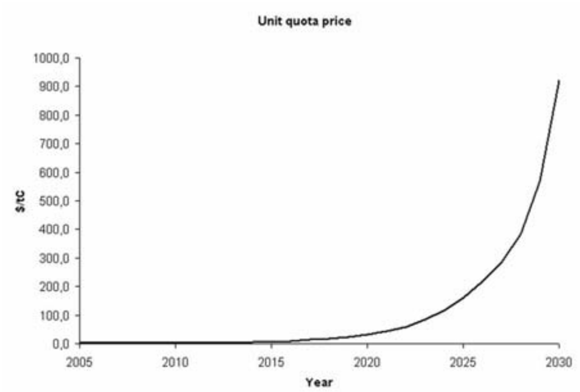

Figure 14. Price development in T0, trial 1.

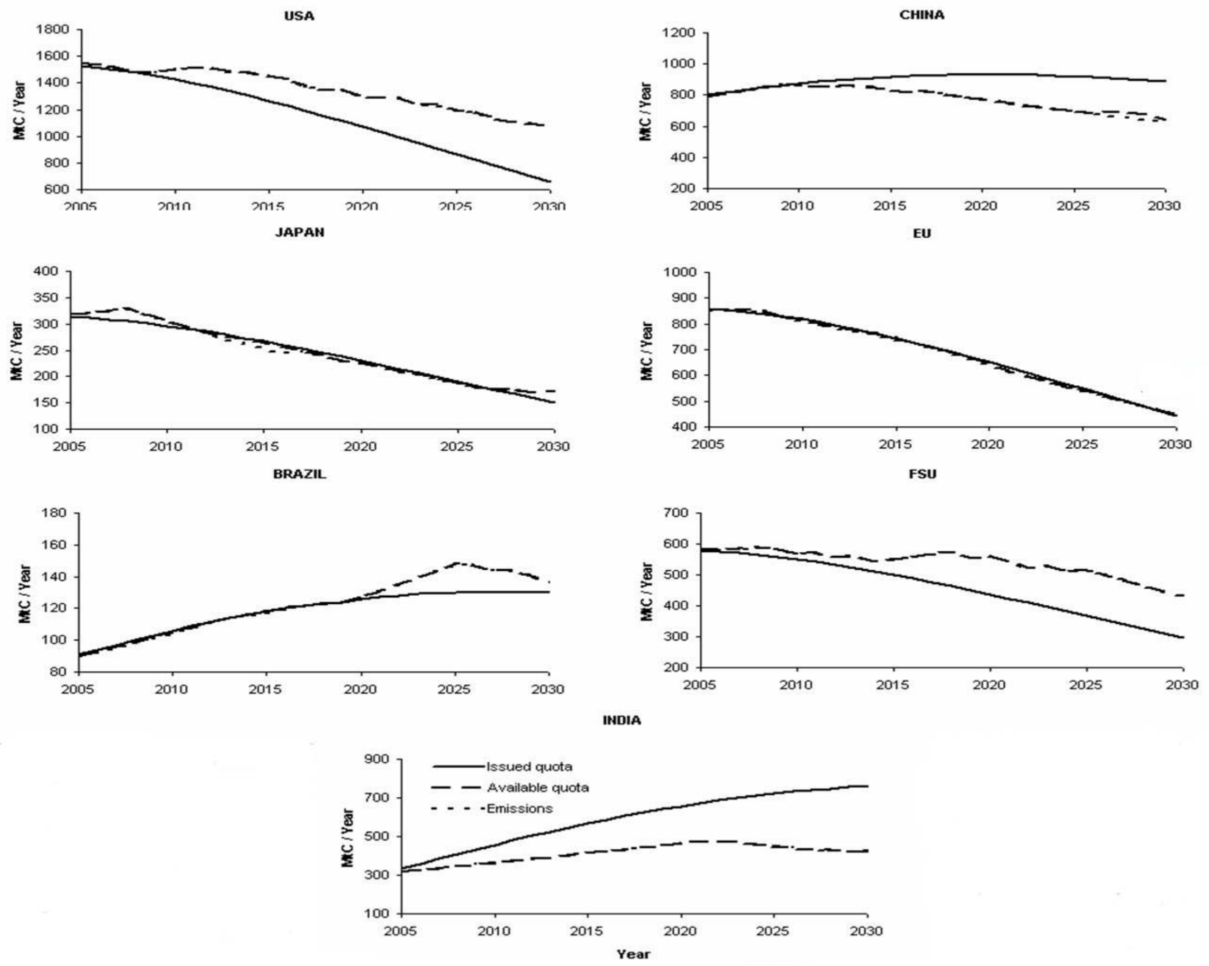

Figure 15. Country behaviors in T0, trial 2.

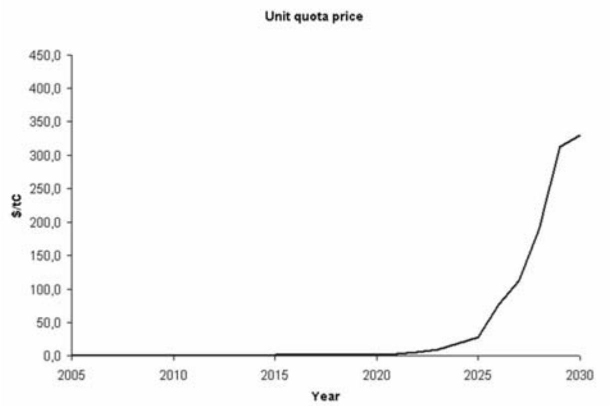

Figure 16. Price development in T0, trial 2.

IV. 5. Results of the Experiments – T1

Emission and price development s for the two trials on T1 are illustrated in Figures 17-20. When both trials are compared to reduction without trade, the net reduction amounts are not altered significantly. In these experiments all buyers, except BRA are worse-off compared to no-trade, hence they cannot benefit from trade (see Table 2).

T1 is also compared to T0, second trial (which was relatively more successful compared to T0 first trial). In both trials, net reduction amounts do not change significantly but net total trade increases. However, all buyers except BRA are worse-off in their net present costs compared to T0 as well. Price development follows different patterns (Figures 18 and 20).

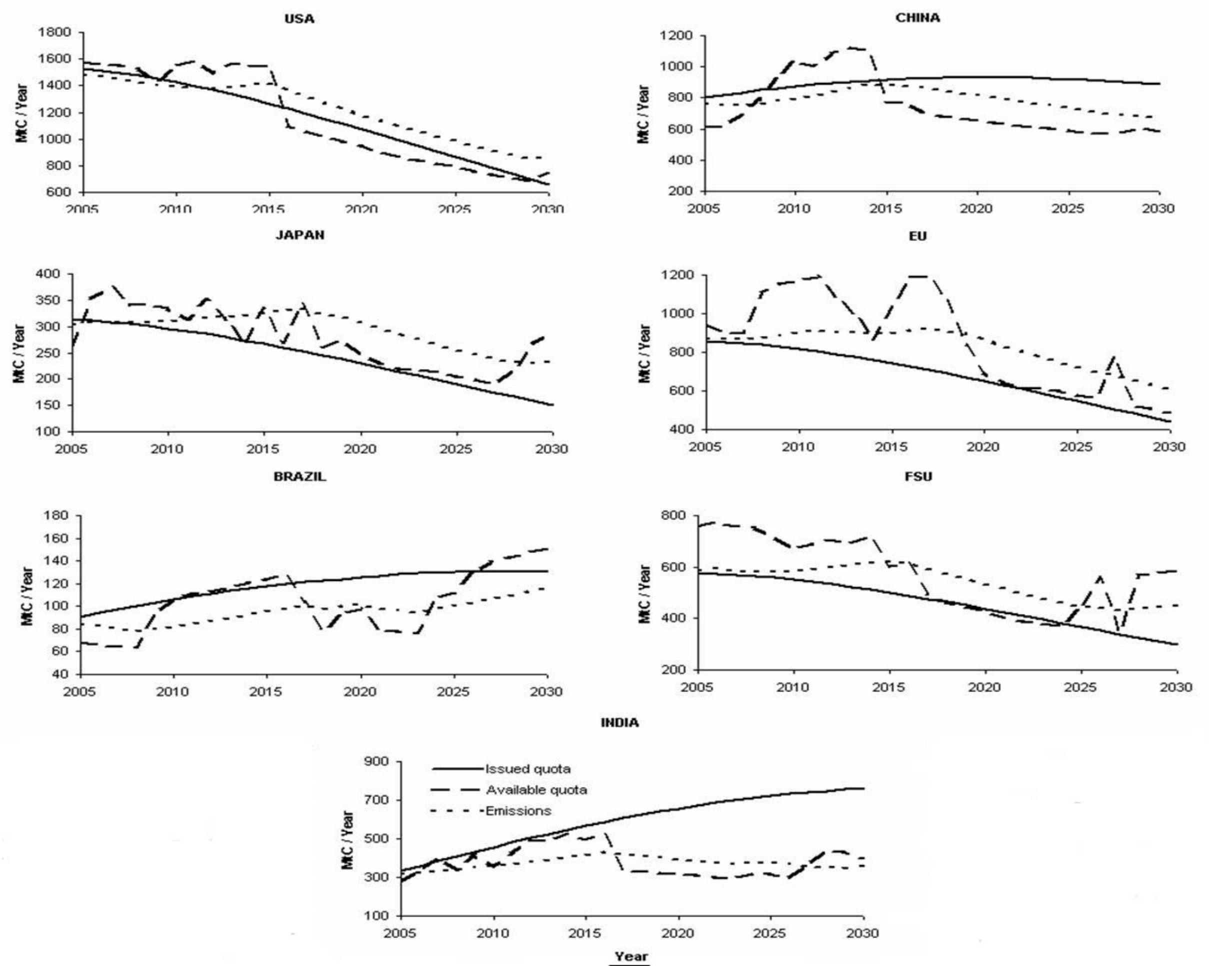

Figure 17. Country behaviors in T1, trial 1.

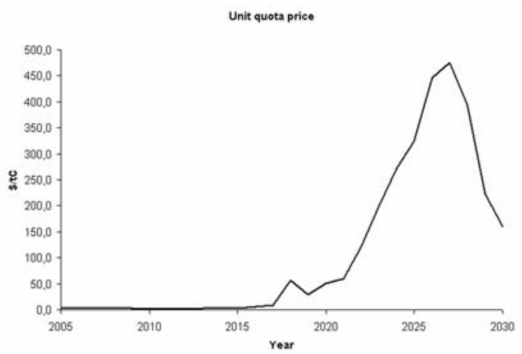

Figure 18. Price development in T1, trial 1.

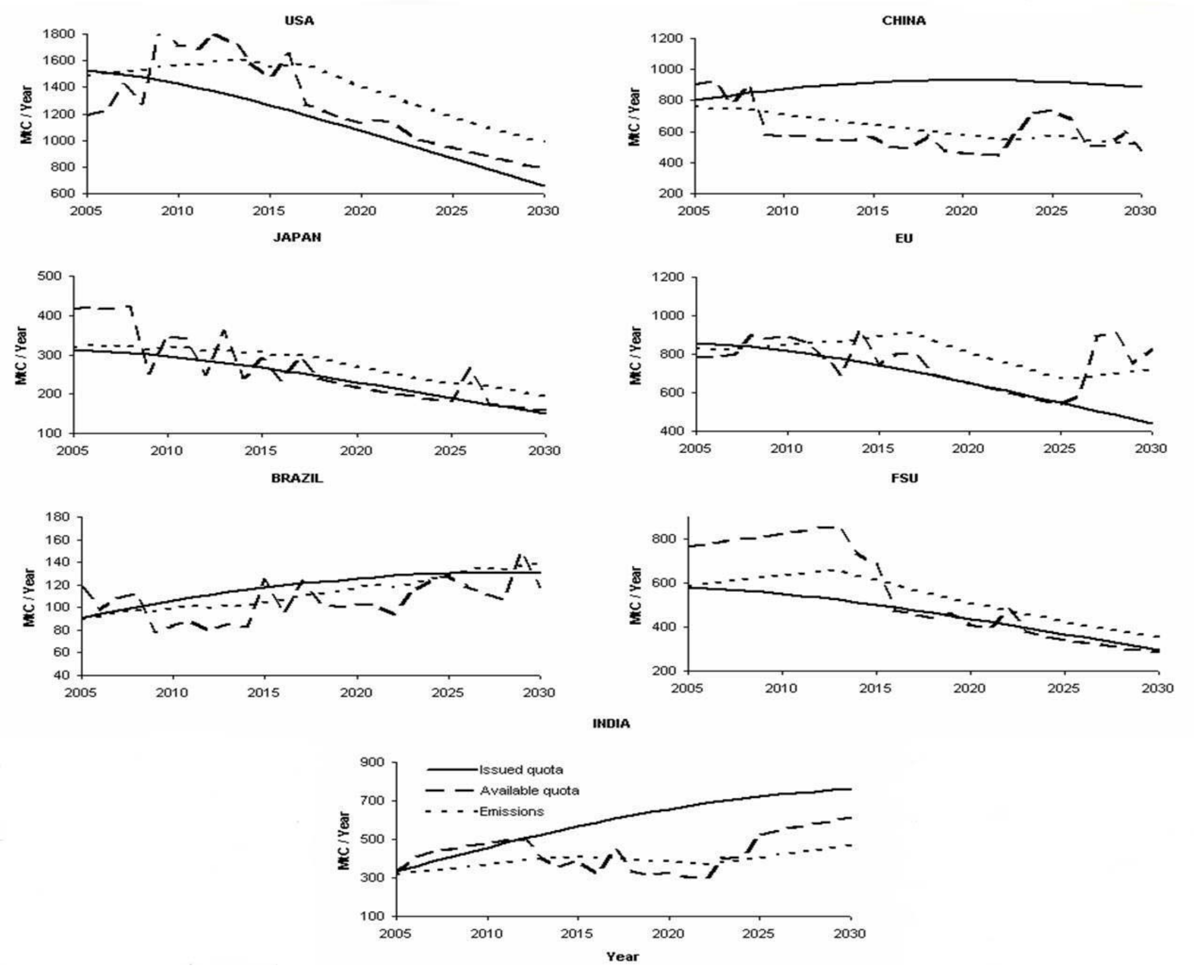

Figure 19. Country behaviors in T1, trial 2.

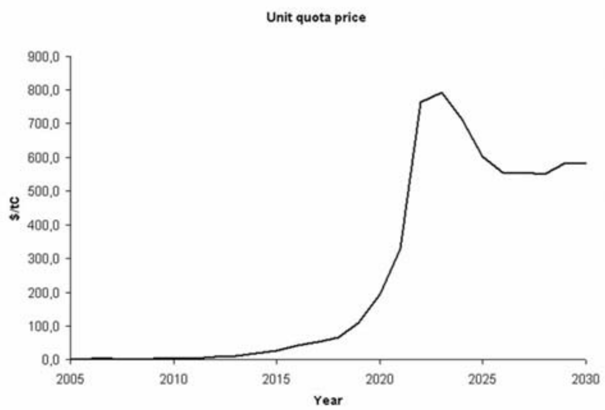

Figure 20. Price development in T1, trial 2.

Region	No Trade		T0-Min				T0-1				T0-2			
	net reduction (MtC)	**net present cost (M$)**	**net reduction (MtC)**	**quota slack (MtC)**	**net total trade (MtC)**	**net present cost (M$)**	**net reduction (MtC)**	**quota slack (MtC)**	**net total trade (MtC)**	**net present cost (M$)**	**net reduction (MtC)**	**quota slack (MtC)**	**net total trade (MtC)**	**net present cost (M$)**
USA	815.3	227,038	257.6	0.6	8,358.7	792,644	611.7	0.1	2,446.8	358,672	421.1	0.6	5,002.9	249,074
China	-134.2	4,418	438.7	0.2	-8,755.7	-741,790	46.9	0.7	-1,623.8	-161,770	119.8	12.8	-2,800.3	-78,108
Japan	151.7	82,078	-23.0	0.4	2,447.5	229,021	15.0	0.9	1,979.4	165,426	141.3	0.1	55.5	81,029
EU	383.0	153,159	27.4	0.4	4,859.0	467,747	287.5	7.2	1,115.1	196,404	377.8	0.1	-51.1	155,264
Brazil	-44.8	12,986	-73.0	0.5	151.4	24,587	-44.5	0.9	-23.9	13,135	-55.5	0.5	103.7	13,077
FSU	260.2	39,885	207.4	0.7	1,160.1	122,545	179.3	0.2	1,426.7	117,916	122.9	0.9	1,981.2	73,033
India	-347.3	0,0	142.9	0.8	-8,221.0	-173,961	-116.6	0.5	-5,320.4	-356,928	-118.1	0.1	-4,292.2	-123,288
TOTAL	1,081.8	519,564	976.0	3.7	16,996.7	720,794	979.3	10.5	6,993.7	333,055	1,009.4	15.1	7,237.9	370,011

Table 1. Results comparison (Year 2030) – T0

Region	T1-Min				T1-Max				T1-1				T1-2			
	net reduction (MtC)	**quota slack (MtC)**	**net total trade (MtC)**	**net present cost (M$)**	**net reduction (MtC)**	**quota slack (MtC)**	**net total trade (MtC)**	**net present cost (M$)**	**net reduction (MtC)**	**quota slack (MtC)**	**net total trade (MtC)**	**net present cost (M$)**	**net reduction (MtC)**	**quota slack (MtC)**	**net total trade (MtC)**	**Net present cost (M$)**
USA	375.0	-218.9	5,563.2	686,699	381.5	-180.3	6,979.5	672,320	660.3	-104.6	1,649.6	377,942	490.0	-196.9	6,046.5	1,265,222
China	195.1	-110.1	-4,441.5	-490,358	235.3	-101.8	-6,127.4	-493,850	77.9	-88.5	-2,772.9	-252,831	232.9	-33.1	-6580.7	-1,154,592
Japan	-1.5	-49.0	1,906.9	224,939	12.4	90.9	1,875.6	188,194	80.3	59.5	1,246.0	158,337	105.7	-38.5	786.7	201,240
EU	84.2	-128.4	3,481.6	433,081	100.6	227.9	3,659.1	342,957	213.2	-122.0	3,469.2	368,924	139.1	110.8	2,869.9	685,035
Brazil	-64.5	-18.7	33.6	16,654	-57.1	45.0	7.8	15,073	-28.0	34.3	-551.0	-14,157	-52.5	-20.5	-134.6	5,465
FSU	223.3	-66.2	415.6	72,038	188.0	-72.8	908.2	109,117	127.3	135.0	2,068.7	203,138	201.9	-70.8	1,780.9	259,312
India	75.2	-43.9	-6,959.5	-754,296	65.6	-45.8	-7,002.8	-640,911	-47.7	39.2	-5,155.5	-493,993	-156.1	142.2	-4,768.7	-974,574
TOTAL	886.7	-635.2	11,742.8	188,757	926.5	-36.9	15,465.6	192,900	1,083.1	-47.2	9,391.1	347,360	960.9	-106.9	12,759.7	2,871,109

Table 2. Results comparison (Year 2030) – T1

V. DISCUSSION AND LIMITATIONS OF THE ANALYSIS

Carbon trading with economic growth in the long term illustrates, potential buyers cannot benefit from trade. When the market size increases with surplus and deficit allowances around annually issued quotas, buyers are even worse-off.

In both trials of T0 buyers tend to reduce early and demand less compared to T0-Min. On the other hand, sellers' tendency to increase rather than sell reduces the supply as well. In the first trial, this generates a price development pattern above T0-Min and creates higher costs for the buyers. In the second trail, similar tendencies are observed with a lower price development but still creating high trade costs for the buyers.

In T1, it is observed that large market for allowances does not help the buyers. These results suggest that, the trade rules and institutions tested in these experiments do not help the viability of a long term cap-and-trade scheme like Contraction and Convergence.

Current experimental design has several limitations. First, the asymmetric structure of the seven player network game makes it costly to bring reasonable amount of data suitable for statistical analysis. Second, it is difficult to calculate the near-optimum behaviors which can serve as a benchmark for analysis. Consequently, the results are descriptive rather than being inferential and conclusive.

Third, the cost structure imposed in the long term has limitations. A better design with endogenous costs of capital replacement and efficiency increase may lead to more reliable results. Last, the delays from the reduction decisions to actual reductions in CO_2 emissions are not considered.

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